EUVE 1'110T0h41T1'll,% 013 SIHWA1'10NS OF COOL STARS

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ABSTRACT We present recent results of extreme ultraviolet (EUV) photometric imaging of cool stars obtained with the *Extreme Ultraviolet Explorer* (EUVE) satellite. These data, covering the 70-- 700 Å band, were obtained during calibration pointings and during the 6 month all-sky survey. Approximately 1/2 of the bright sources detected by EUVE during the survey arc coo] stars of all spectral types. We discuss the determination of coronal temperatures and emission measures using filter ratios, time variability results for a number of RS CVn systems and flare stars, and an analysis of quiescent emission from a sample of dM and dMe stars.

INTRODUCTION

The extreme ultraviolet (EUV) region is a kcy portion of the electromagnetic spectrum for studying the outer atmospheres of cool stars. X-ray observations with *Einstein*, EXOSAT and ROSAT have shown that almost all late-ty])c stars arc soft X-ray sources. This X-ray emission is predominantly from coronal material with temperatures > 3 x 106 K. Ultraviolet observations with the *International Ultraviolet Explorer* (IUE) and the *Hubble Space Telescope (11S'1')* have been used Lo study the chromospheres and transition regions of many late-type stars, where the temperatures arc $\leq 3 \times 10^5$ K. But the material in stellar outer

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atmospheres with temperatures between 105 K and ~ 3 x 106 K has not been well studied. As shown by synthetic spectrum models (Raymond and Smith 1977; Landini and Monsignori-Fossi 1990), the emission at these temperatures is principally in the extreme ultraviolet. The EUV therefore represents a key missing piece in our understanding the overall temperature structure and energetics of the atmospheres of cool stars, bridging the gap between cooler and hotter material.

Broad-band photometric observations taken with the Extreme *Ultraviolet Explorer* (EUVE) satellite present an unique, new data set for studying cool **stars.** The *Wide Field Camera* (WFC) *on* ROSAT provided the first hint at the emission of cool stars at the shortest EUV wavelengths during its all-sky survey in 1990. EUVE for the first time provides information spanning the entire EUV range from 70 - 700 Å. The EUVE photometry data enables us to study many cool stars with a range of intrinsic brightnesses, allowing us to better examine of the numbers of objects emitting in the EUV, their spectral type distribution, luminosity distribution, spatial distribution, rough coronal temperatures and variability.

EUVE PHOTOMETRIC OBSERVATIONS

The EUVE satellite, launch in June 1992, contains four grazing incidence telescopes (Bowyer and Malina 1990). Three co-aligned Scanner telescopes enable photometric measurements in four bandpasses covering the EUV region. The fourth Deep Survey/Spectrometer (DS/S) telescope, in addition to providing EUV spectroscopic measurements, also has two photometric bandpasses covering the shorter EUV wavelengths. The EUVE bandpasses are listed below in Table I.

TABLE 1 EUVE Photometric Bandpasses

Instrument	Filter	10 % Bandpass	λ
Scanner	Lexan/B	50- 180 Å	100 Å
	Al/Ti/C	160- 240 Å	180 Å
	Ti/Sb/Al	345 - 605 Å	400 Å
	Sn/SiO	500-- 740 Å	550 Å
DS/S	Lexan/B	65 - 190 Å	100 Å
	Al/C	160- 360 Å	180 Å

Photometric data on cool stars obtained with EUVE are of two basic types: all-sky survey observations and pointed observations. The all-sky survey was completed in August 1993 (Malina et al. 1993). For a given object, the survey data comprises 10--20 seconds of observational exposure every 96 minutes, as the spacecraft spins to survey the entire sky. The total exposure times for the all-sky survey ranges from 400 s near the ecliptic equator to about 20,000 s near the ecliptic poles. Thus far, only the all-sky survey data have been searched carefully for point sources. The simultaneous deep survey, with exposure times of 20,000 s on average, lower sky background, and enhanced sensitivity has not been explored in detail.

Pointed observations of cool stars include both calibration pointings and pointed spectroscopic observations of Guest Observer (GO) targets. During GO target pointings, broad-band imaging data is obtained simultaneously in the 100 Å Lexan/B bandpass. These pointed observations typically have total exposure times of 20,000 - 100,000 s broken up into 30 minutes of continuous observation every 96 **minutes.**

The first Bright Source List (BSL) of objects detected in the EUVE survey contains 356 extreme ultraviolet sources (Malina et al. 1993). Cool stars are prominent amongst these sources, with 172 late-type stars in the BSL, representing 48% of the total number of objects, and covering all spectral types. A similar number and percentage of cool stars were detected in the first ROSAT WFC catalog (Pounds **et** al. 1992). The breakdown by spectral type of cool stars in the EUVE BSL is 31 F stars, 67 G stars, 43 K stars and 37 M stars. These include RS CVn systems and binaries. Pointed calibration observations have been obtained of about 10 cool stars, and Guest observer pointed observations of late-type sources are increasing daily.

Beyond simply the knowledge that a given cool star is or is not an EUV source (to the sensitivity level of the survey), there are several additional aspects that one can hope to glean from the EUVE photometric data. Three of these topics are discussed below: determination of coronal temperatures, variability and statistical samples of objects.

TEMPERATURES FROM EUV PHOTOMETRY

One of the most desirable pieces of information that might be derived from the EUVE photometry data are details about the temperatures of the EU - emitting material in cool stars. As discussed in the Introduction, the EUV spectral region samples a large and important temperature regime in the outer atmospheres of cool stars, with numerous, bright emission lines (e.g., Jordan 1991). The broad band X-ray fluxes measured with *Einstein* and EXOSAT have been used previously to determine rough coronal temperatures using filter ratios (e.g., Pallavicini **et** al. 1988; Schmitt and Rosso 1988). This same technique could, in principal, be used to constrain coronal temperatures for objects with fluxes measured in multiple EUVE bandpasses.

Unfortunately, this technique is difficult in practice with the EUVE data set. The majority of cool stars are detected only in the two shortest wavelength EUVE bandpasses, the Lexan/B and Al/Ti/C filters, and the temperature sensitivity of these **two** filters is extremely similar. The Lexan/B band is most sensitive to emission from coronal material at temperatures of $\sim 3 \times 10^5$ K to $\sim 2 \times 10^6$ K, while the Al/Ti/C band sensitivity is dominated by material in the range $\sim 6 \times 10^5$ K to $\sim \mathbf{2} \times 10^6$ K. This does not allow the coronal temperatures to be significantly constrained if only those two bandpass fluxes are available, and multiple temperature solutions are typically allowed (e.g. Vedder et al. 1993; Patterer et al. 1993). An accurate knowledge of column density to the source also can play a major role.

The best temperature determination to date using EUVE photometric data has been for α Cen (G2V + K1V), which was detected in all four Scanner bandpasses (Vedder et al. 1993). When combined with previous *Einstein* IPC and IUE measurements, they found the EUVE fluxes to be consistent with two temperature components: $T_1 = 8.5 \times 10^5$ K with $EM_1 = 1.5 \times 10^{50} cm^{-3}$ and $T_2 = 10^5$ K with $EM_2 = 5 \times 10^{49} cm^{-3}$. These results indicate that the emission measure distribution for α Cen is much steeper than previously thought, with $EM \propto T^3$ rather than the $EM \propto T^{3/2}$ dependence expected for normal cool stars (Jordan 1991).

Although the results for α Cen suggest that temperature constraints can be derived in some cases, the determination of temperatures for the EUV emitting material in cool stars can be done much more definitively and easily using individual emission lines in EUV spectra (see Alex Brown's review in these proceedings) rather than with photometric fluxes.

EUV VARIABILITY

Studies of time variability in cool stars are an important capability of photometric observations. Variability has long been studied in the visible and in X-rays, but the EUVE and WFC data provide the first opportunity to examine variability at extreme ultraviolet wavelengths. This allows a careful study of the temporal behavior and energetics of the atmospheres of cool stars.

Several types of variability have been observed in late-type stars with EUVE: flaring, rotational modulation and eclipsing. The best data, particularly for shorter period phenomenon like flaring, come from the long duration calibration and Guest Observer pointings, which have long un-interrupted observing periods (30 minutes). The EUVE survey data have a difficult duty cycle of 10- 20 seconds of data every 96 minutes, but can cover anywhere from 5 to 180 days. This is very useful for studying longer term variations in objects.

Flaring

The most spectacular and well-studied EUV flare to date from a cool star has been the large event observed on AU Mic (dM1e) in July 1992 (Cully et al. 1993; Cully, Fischer and Siegmund 1994; Monsignori-Fossi, Landini and Bowyer 1994). During this event, which actually comprises a large and a small flare, the EUV count rate in the 100Å Lexan/B band increased by a factor of seven, making it one of the brightest EUV objects in the sky. One of the unique aspects of this observation is that simultaneous spectroscopy data was obtained, allowing a detailed time-dependent study of the temperture structure. The larger of the two flares had a peak luminosity of 10^{30} ergs s^{-1} and lasted for approximately 36 hours.

A number of other cool stars, primarily well-known flare star systems, have been observed by EUVE while flaring. They include AT Mic (dM4.5e + dM4.5e; although a spacecraft safe-hold produced a gap in data during the decay precluding quantitative results), Prox Cen (dM5e), YZ CMi (dM4.5e), AD Leo (dM3.5e; Hawley 1993) and II Peg (RS CVn). These EUV flares cover a range of peak luminosities, total energies and decay durations, which are summarized in Table II. For the II Peg flare, which was inferred from a pointed calibration observation (Patterer et al. 1993), the flare peak occurred before the observation began, so no quantitative data is available.

TABLE 11 Flares Observed by EUVE to Date

	Peak $L^{\dagger}_{EUV}$	Total $E^{\dagger}_{EUV}$	Duration
AU Mic #1	1×10^{30} ergs/s	3×10^{34} ergs	36 111's
AU Mic #2	6×10^{29} ergs/s	2×10^{33} ergs	3 hrs
Prox Cen	9×10^{26} ergs/s	3×10^{30} ergs	2 111's
YZ CMi	7×10^{28} ergs/s	8×10^{32} ergs	13 hrs

† for 100 Å Lexan/B band

One important flare observed by EUVE occurred on Prox Cen in July 1992. Prox Cen was observed *simultaneously* in both the 100 Å Lexan/B and the 180 Å Al/Ti/C bandpasses during a pointed calibration observation. The flare event was detected in the Lexan/B filter but not in the Al/Ti/C filter (see Figure 1). An emission measure analysis of this event (Vedder et al. 1994a) indicates that in quiescence, the E UV emission from Prox Cen is due Lo cooler material between 2 x 10^5 K and 3 x 10^6 K. During the flare, the emission is from material between 5 x 10^6 K and 2 x 107 K. This demonstrates that the increase in EUV radiation during this flare event is dominated by an increase in the temperature of the emitting heating rather than an overall increase in total emission measure, as has been suggested previously by Dupree and Kenyon (1991) and Haisch et al. (1983).

Eclipsing

A second type of variability phenomenon observed in]at(!-type stars by EUVE has been eclipsing in the AR Lac RS CVn system. AR Lac contains a G2 IV primary which is totally eclipsed by a 1<0 IV secondary with a 1.983 day period. During a day-long pointed observation in June 1992, the AR Lac primary was eclipsed, with a corresponding reduction in the EUV count rate in the Lexan/B band. An analysis of the light curve by Patterer et al. (1 994a) indicates that the data arc consistent with equal EUV emission from both components in the AR Lac system. A similar EUV flux was observed from AR Lac during the survey in December 1992, suggesting a long-term stability in the level of EUV emission from this RS CVn.

Rotational Modulation

Variability in EUV emission duc to rotational modulation has been detected by EUVE on HR 1099 (= V711 Tau; K] IV + G5 V, P=2.84 days). HR 1099 was observed for 5 days during the all-sky survey in August, 1992 and then again for 3 days during a pointed calibration observation in October 1992. Both observations were longer than the 2.84 day rotational period. In both data sets, there is evidence for Inoculation in the 100 Å EUV flux, with similar phase behavior (Drake et al. 1994). The level of modulation is about 40%, with the minimum flux level occurring near phase $\phi \approx$ ().5 and the maximum flux level occurring near phase $\phi \approx 0.0$. Simultaneous optical Stromgen *b* photometry indicates an anti-correlation between the EUV and optical light curves. The interpretation of these data is that the EUV emission is due to a long-lived,

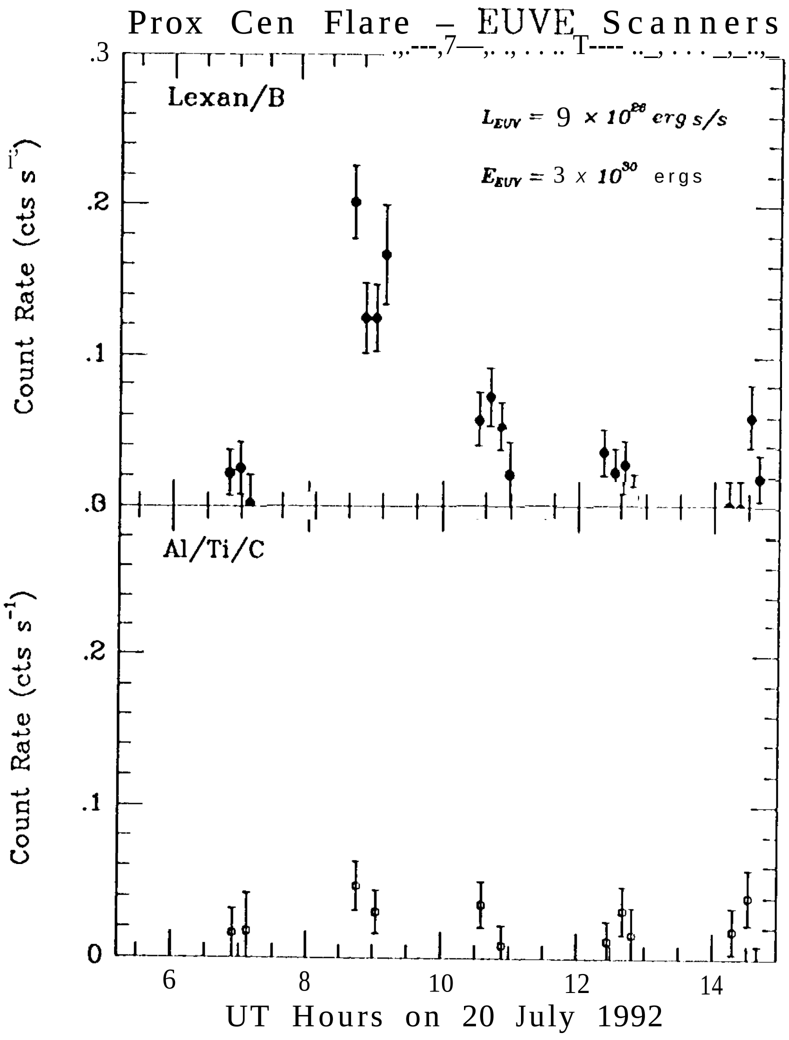

FIGURE I Flare observed on Prox Cen by EUVE in July 1992 compact, and bright corona] structure on the more active component in the system.

SAMPLES OF OBJECTS

One area where broad-band photometric data play a singular and important role arc in statistical studies of samples of objects. This is particularly true for data sets of large numbers of objects, such as the EUVE and WFC all-sky surveys. These allow not only detections, but upper limits as well, to be included in studying the characteristics of EUV emission in cool stars.

The examination of various samples of coo] star's, such as by spectral Lypc (F stars, G stars, K stars, etc.), or volume-li]rlitcd samples, are planned for the near future using the EUVE survey data. A few coo] stars samples arc already being studied: RS CVn's (Patterer et al. 1994b),]atc-type stars with low activity levels (Mathioudakis et al. 1994), and flare stars (Vedder CL al 1994b). As an example of the findings Lo date, we discuss the results for a sample of flare stars observed with EUVE.

The flare star sample consists of 47 nearby stars which have been observed Lo flare, taken from the list of Pettersen (1991). Nearly 2/3 of the stars (29 out of 47 objects) were detected as EUV sources. Within the sample, most of the dMe stars were detected as EUV bright (25 OUL of 29), but few of the dM stars were detected (only 1 out of 13 stars). This suggests that the active dMe stars may have a detectable baseline level of corona] EUV emission while the inactive dM stars have very weak coronae (at least in the EUV). There is also evidence for saturation of Lhc EUV surface flux for earlier spectral types, leveling off at just under 107 ergs cm^{-2} s^{-1} (see Figure 11).

There is also a strong correlation between the EUV and X-ray luminosities of these flare stars, despite the data coming from non-contemporaneous observa - tions. This is most likely duc to the EUV and X-ray photons both being emitted from the same temperature regime in the star. IL also indicates that there were no strong flares observed during the EUV or X-ray observations, and that emission is dominated by a constant coronal emission rat her t ha n occasional large flares. Further results will be fort hcoming in Vedder et al. (1994b).

THE FUTURE

The EUVE broad-batld photometry data arc a unique scientific asset, and there arc a number of exciting projects on cool stars that can and will be done in the near future. As mentioned above, statistical studies of various samples of COO] stars arc already underway, including producing EUV luminosity functions. Variability studies, particularly searching for longer-])criod variations such as rotational modulation or activity level variations, can be examined using the survey data. The EUVE survey data can be compared to t he I{ OS Al" WFC results to examine EUV flux levels over a 2 year baseline. A more complete analysis of the deep survey data set, with a factor of 10 greater' sensitivity than the all-sky survey, promises to greatly increase the number of cool stars detected as EUV sources, particularly the numbers of fainter objects. And a thorough

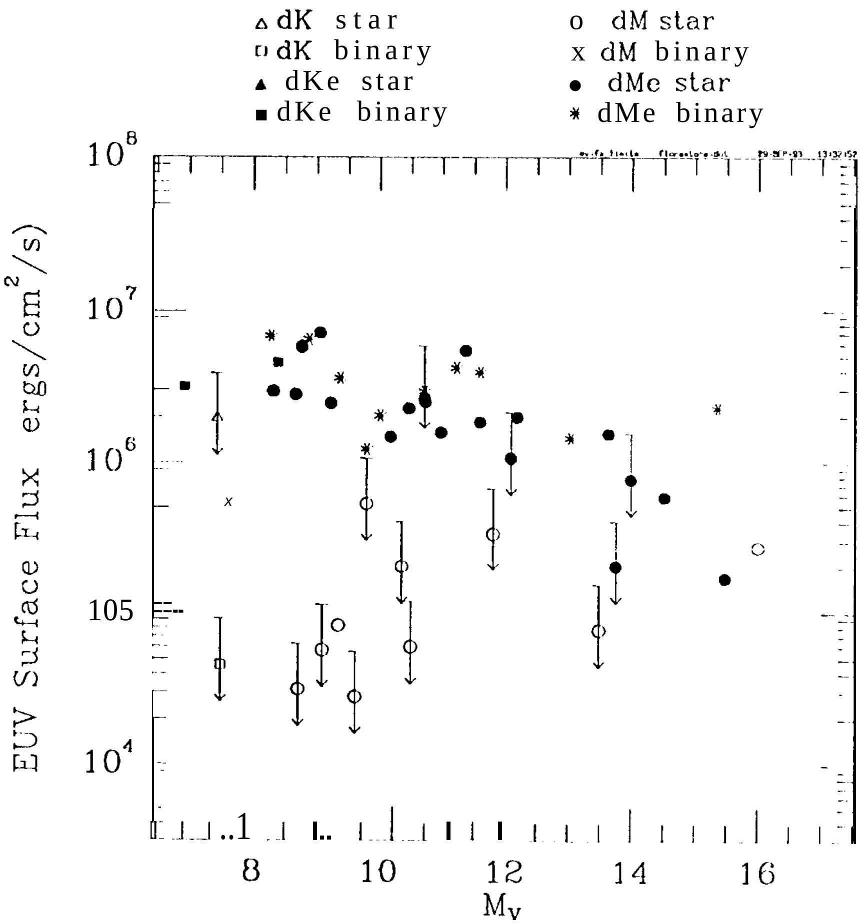

FIGURE 11 The EUV surface flux for the flare star sample in the 100 Å Lexan/B band as a function of absolute magnitude. The key to individual spectral type is at top.

culling Of the E UVE survey skymaps to produce a catalog of EUV fluxes (01' limits) for a large number of late-type stars will also be useful to researchers.

One aspect worth mentioning in closing is that even though the all-sky survey is completed, broad-band photometry of cool stars continues to be collected every day by EUVE. These **data** come in two main forms. The first are the broad-band images of Guest observer targets obtained simultaneously with their spectra] observations. These longer exposures allow significantly better studies of flaring and variability in selected cool stars than is possible from the survey data.

'l'he second form of new cool star data arc the images taken by the Scanner telescopes during a Guest observer pointing. The EUVE Scanner detectors remain on, collecting data during spectroscopic observations with the 1) S/S telescope. They point in random directions orthogonal to the GO target, accumul - ing long exposure up **Lo 300,000 s** in some **cases.** To **date,** these Scanner images **have** revealed **an average** of two *new* EUV sources during each GO pointing as part of this "right angle program". If WC expect 50% Of these objects to be coo] stars, the same percentage as for the survey, wc can anticipate new EUV data on about 100 cool stars each year. Many will be fainter objects, and the longer exposures will enable careful variability studies as well. So for exciting, new results from E UVE photometry data, it is likely that the best, is yet to come.

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